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19. ABSTRACT (Continue on reverse if necessary and identify by block number)

In this study, a 39 page long list of pulse power formulae was prepared for use by workers in the pulse power field. The categories of formulas and data presented includes: fundamental constants, unit conversions, model circuit results, marx generator circuits, capacitor charging circuits, transformer circuits, magnetic switching, transmission line circuits, transmission line geometric relationships, skin depth, field enhancement factors, solid, liquid and gaseous dielectric properties, intense electron and ion beam physics, electron beam/matter interaction, high power microwaves, railguns, diagnostics, and mechanical data. Vest pocket sized versions of this formulary are being widely distributed.

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FINAL REPORT, PULSE POWER FORMULARY

CONTRACT F49620-89-C-0005

PREPARED BY: NORTH STAR RESEARCH CORPORATION

SEPTEMBER 23, 1989

The formulary project has been completed with, to our mind, excellent results. Since the main task is formulary development, we include the formulary as printed in full size form in this report. We note that the formulary was completed at a cost which was 18 % under the originally allotted budget, with the level of effort still satisfying the initial requirements.

As of this writing, we have distributed copies of the formulary to all of the major US pulse power laboratories of which we are aware. These laboratories include:

Sandia National Laboratories
Lawrence Livermore National Laboratories
Los Alamos National Laboratories
Wright Paterson Air Force Base
Westinghouse Research
State University at New York (Buffalo)
Physics International Company
Defense Nuclear Agency
Harry Diamond Laboratories
ETDL, Fort Monmouth
Air Force Weapons Laboratory
Texas Tech. University
Naval Surface Weapons Center
Naval Research Laboratory
University of Texas, Center for Electromechanics
Hughes Research Laboratory
Pulse Sciences, Inc.
Titan Corp.
Rockwell International
Cornell University
University of Maryland
Varian Associates
Maxwell Laboratories, Inc.

We also plan to offer copies of the formulary to be handed out at the registration of the next pulsed power conference and modulator symposium.

The formulary was reviewed by the contributors: I.D Smith of Pulse Sciences, Inc., R.C. Noggle of Rockwell Power Systems, and G.F. Kiuttu of MRC. Dr. D. Mitrovich of NSRC also reviewed the document extensively in the areas of units, and differential equation solutions. At the time at which the actual review was required, R. Reinofsky and K.R. Prestwich were unable to review the document as originally planned.

Section 2.0 of this document is a copy of the formulary, and a number of the vest pocket sized formularies are also enclosed in the same package as the final report.

REFERENCES IN THE DATABASE AS THEY APPEAR

SEC	TITLE	AUTHOR	JOURNAL	VOL	PG	YR
1.0	Ref. Data for Radio Eng.	H.W. Sams	H.W. Sams		3-11	1975
1.0	NRL Plasma Formulary	D.L. Book	NRL		14	1983
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3.4	High Volt. Impulse System	Finkelstein	Rev. Sci. Inst.	37	159	1966
3.4	Transformer Type Accels.	E.A. Abramyan	IEEE T Nucl. Sci.	NS-18	447	1971
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4.2	High Voltage Cable PFL	R. Limpaecher	IEEE Mod. Symp.		264	1986
4.2	Design of Hermes III	T.H. Martin	IEEE T Nucl. Sci.	NS-16	59	1976
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2.0 FORMULARY

NOTE THAT THE PAGE NUMBERING SHOWN IN THE FOLLOWING PAGES IS EXACTLY AS IT APEARS IN THE FORMULARY ITSELF

PULSE POWER FORMULARY

Richard J. Adler

North Star Research Corporation

August, 1989

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Supported by

The Air Force Office of Scientific Research

Introduction

The purpose of this document is to serve the user of pulse power in the variety of tasks which he or she faces. It is intended to be used as a memory aid by the experienced pulse power engineer, and as a record of pulse power facts for those with less experience in the field, or for those who encounter pulse power only through their applications. A great deal of pulse power work involves the evaluation of distinct approaches to a problem, and a guide such as this one is intended to help speed the calculations required to choose a design approach.

In the formulary, we strived to include formulae which are 'laws of nature' such as the circuit equations, or well established conventions such as the color code. We have purposely avoided listing the properties of commercial devices or materials except where they may be regarded as generic. This has been done so that the formulary will not become obsolete too quickly. The formulas have intentionally been left in their original form, so that the use of the formulary tends to reinforce one's natural memory.

We hope, in future, to expand this document, particularily by adding new applications areas. A section on prime power systems would also be desirable. Any suggestions on formulas which have been omitted or misprinted would be appreciated.

The author would also like to thank W. Dungan and B. Smith of the US Air Force, W. Miera of Rockwell Power Systems, and J. Bayless and P. Spence of Pulse Sciences, Inc. for encouragement over the course of this and previous formula compilation efforts.

Finally, we note that few written works are without error, and that even correct information can be misinterpreted. North Star Research Corporation and the US Air Force take no responsibility for any use of the information included in this document, and advise the reader to consult the appropriate references and experts in any pulse power venture.

This work was supported by the US Air Force Office of Scientific Research under contract F49620-89-C-0005.

1.0 FUNDAMENTAL CONSTANTS

Nomenclature: note that numbers in brackets are base 10 exponents

Example: $1.26 \times 10^{-6} = 1.26(-6)$

SYMBOL	NAME	VALUE-MKS(exp)	VALUE-CGS(exp)
c	Speed of light	2.9979(8)m/s	2.9979(10)cm/s
e	Electron charge	1.6022(-19)C	4.803(-10)esu
ϵ_0	Free Space Permittivity	8.8541(-12)F/m	1
μ_0	Free Space Permeability	1.2566(-6)H/m	1
h	Planck's Constant	6.6261(-34)J-S	6.6261(-27)erg-s
m_e	Electron mass	9.1094(-31)kg	9.1094(-28)g
m_p	Proton mass	1.6726(-27)kg	1.6726(-24)g
amu	Atomic mass unit	1.6605(-27)kg	1.6605(-24)g
e/m_e	Electron charge/mass	1.7588(11)C/kg	5.2728(17)esu/g
m_p/m_e	p/e mass ratio	1.8362(3)	
k	Boltzman constant	1.3807(-23)J/K	1.3807(-16)erg/K
N_B	Avogadro constant	6.0221(23)mol^{-1}	
σ	Stefan-Boltzman constant	5.671(8)W/m^2K^4	5.671(-5)
n_0	Loschmidt constant	2.6868(25)m^{-3}	2.6868(19)cm^{-3}
atm	Standard Atmosphere	1.0132(5)Pa	1.0125(6)erg/cm^3
g	Gravitational Const.	9.8067Kgm/s^2	9.8067(5)gcm/s^2

Units:

m = meter; cm = centimeter; s = second; q = coulomb = Amp-s

esu = electrostatic unit; F = Farad; H = henry; J = Joule = $kg\text{-}m^2/s^2$

kg = kilogram; g = gram; erg = $g\text{-}cm^2/s^2$

K = degree Kelvin; Pa = Pascals = Kg/ms^2

Energy Equivalence Factors

1 kg = 5.610(29) MeV   1 amu = 931.48 MeV   1 eV = 1.602(-19) J

$\lambda(m)$ = 1.2399(-6)/E(eV)

2.0 DIMENSIONS AND UNITS

MKS units are generally used in pulse power, with Gaussian units preffered in some applications. In order to convert a number in MKS units into gaussian units, multiply the MKS number by the Gaussian conversion listed. The number 3 is actually related to c and for accurate work is taken to be 2.9979. In this work numbers in parentheses are base 10 exponents.

Physical Quantity	Symbol	Dimensions SI(MKS)	Dimensions Gaussian	SI Units	Gaussian Conversion	Gaussian Units
Capacitance	C	$t^2q^2/m\ell^2$	ℓ	farad	9(11)	cm
Charge	q	q	$m^{1/2}\ell^{3/2}/t$	coulomb	3(9)	statcoul.
Conductivity	σ	$tq^2/m\ell^3$	$1/t$	siemens/m	9(9)	sec^{-1}
Current	I	q/t	$m^{1/2}\ell^{3/2}/t^2$	ampere	3(9)	statamps
Density	ρ	m/ℓ^3	m/ℓ^3	kg/m^3	1(-3)	$gm./cm^3$
Displacement	D	q/ℓ^2	$m^{1/2}/\ell^{1/2}t$	$coul./m^2$	$12\pi(5)$	$stat\text{-}coul./cm^2$
Electric field	E	$m\ell/t^2q$	$m^{1/2}/\ell^{1/2}t$	volt/m	(1/3)(-4)	statvolt/cm
Energy	U,W	$m\ell^2/t^2$	$m\ell^2/t^2$	joule	1(7)	erg
Energy density	w,ϵ	$m/\ell t^2$	$m/\ell t^2$	$joule/m^3$	10	erg/cm^3
Force	F	$m\ell/t^2$	$m\ell/t^2$	newton	1(5)	dyne
Frequency	f	t^{-1}	t^{-1}	hertz	1	hertz
Impedance	Z	$m\ell^2/tq^2$	t/ℓ	ohm	(1/9)(-11)	sec/cm
Inductance	L	$m\ell^2/q^2$	t^2/ℓ	henry	(1/9)(-11)	sec^2/cm
Length	ℓ	ℓ	ℓ	meter(m)	1(2)	cm
Magnetic intens.	H	$q/\ell t$	$m^{1/2}/\ell^{1/2}t$	amp-turn/m	$4\pi(-3)$	oersted
Magnetic induction	B	m/tq	$m^{1/2}/\ell^{1/2}t$	tesla	1(4)	gauss
Magnetization	M	$q/\ell t$	$m^{1/2}/\ell^{1/2}t$	amp-turn/m	1(-3)	oersted
Mass	m,M	m	m	kilogram	1(3)	gram(g)
Momentum	p,P	$m\ell/t$	$m\ell/t$	kg-m/sec	1(5)	g-cm/sec
Permeability	μ	$m\ell/q2$	1	henry/m	$1/4\pi(7)$	-
Permittivity	ϵ	$t^2q^2/m\ell^3$	1	farad/m	$36\pi(9)$	-
Potential	V,Φ	$m\ell^2/t^2q$	$m^{1/2}\ell^{1/2}/t$	volt	(1/3)(-2)	statvolt
Power	P	$m\ell^2/t^3$	$m\ell^2/t^3$	watt	1(7)	erg/sec
Pressure	p	$m/\ell t^2$	$m/\ell t^2$	pascal	10	$dyne/cm^2$
Resistivity	ρ	$m\ell^3/tq^2$	t	ohm-m	(1/9)(-9)	sec
Temperature	T	K	K	Kelvin	1	Kelvin
Thermal cond	κ	$m\ell/t^3K$	$m\ell/t^3K$	watt/m-K	1(5)	erg/cm-sec-K
Time	t	t	t	sec.	1	sec.
Vector pot.	A	$m\ell/tq$	$m^{1/2}\ell^{1/2}/t$	weber/m	1(6)	gauss-cm
Velocity	v	ℓ/t	ℓ/t	m/sec	1(2)	cm/sec

2.1 MKS-CGS-English Mechanical Unit Conversions

Multiply English value by "Conversion" to obtain value in MKS units.

Quantity	MKS(SI)	English	Conversion
Length	m	foot (ft)	0.305 m/ft
Mass	kg	slug	14.593 kg/slug
Time	sec	sec	
Linear velocity	m/sec	ft/sec	0.305 m/ft
Angular velocity	rad/sec	rad/sec	
Linear momentum	kg-m/sec	slug-ft/sec	0.00430
Linear acceleration	m/sec^2	$ft./sec^2$	0.305
Angular acceleration	rad/sec^2	rad/sec^2	
Force	Newton	pound (lb)	4.4481 nt/lb
Work	Nt-m	ft-lb	1.356 Nt /lb-ft
Energy	Joule	ft-lb	1.356 J/ft
Power	watt	horsepower	747 W/hp
Weight	Kilogram	lb.	0.4536

2.2 Color Code

Color	Number or Tolerance (%)	Multiplier
Black	0	1
Brown	1	10
Red	2	100
Orange	3	1000
Yellow	4	10,000
Green	5	100,000
Blue	6	1,000,000
Violet	7	10,000,000
Gray	8	100,000,000
White	9	1,000,000,000
Silver	[illegible]	0.01
Gold	[illegible]	0.1

Resistors:

First band = first digit
Second band = second digit
Third band = multiplier (or number of zeroes)
Fourth band = tolerance

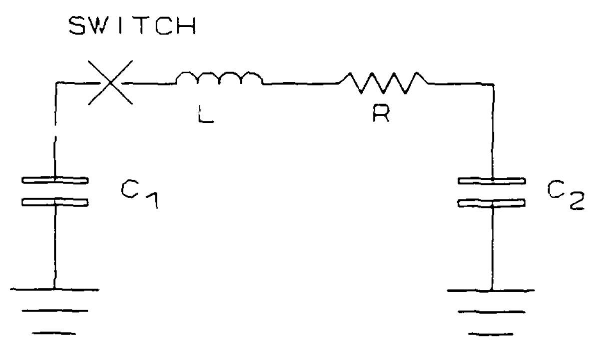
3.0 CIRCUIT EQUATIONS

3.1 Model Circuit Results

3.1.1 LRC Circuit with Capacitor Charged Initially

This is the basic pulse power energy transfer stage, and so is solved in detail. An important limit is the LRC circuit with a single charged capacitor, and that circuit is the $C_2 \to \infty$ limit of the 2 capacitor circuit.

$\tau = L/R$
$C = C_1C_2/(C_1 + C_2)$
$\omega_0^2 = 1/LC$
$\omega^2 = ABS(1/LC - 1/(2\tau)^2)$
V_0 = initial capacitor voltage



1) Oscillatory Case

$R^2 < 4L/C$ (underdamped)

$I = (V_0/\omega L)e^{-t/2\tau}\sin\omega t$

$I(\text{maximum}) \simeq V_0/((L/C)^{1/2} + 0.8R)$

$V(C_2)$ = 'output voltage'
$= [V_0C_1/(C_1 + C_2)]\{1-e^{-t/2\tau}\cos\omega t + (1/2\omega\tau)e^{-t/2\tau}\sin\omega t\}$

$V(C_1) = V_0C_1/(C_1 + C_2) + V_0C_2e^{-t/2\tau}(\cos\omega t + (1/2\omega\tau)\sin\omega t)/(C_1 + C_2)$

$V(C_2 \text{ maximum}) = [V_0C_1/(C_1 + C_2)]\{1-e^{-\pi/2\omega\tau}\}$

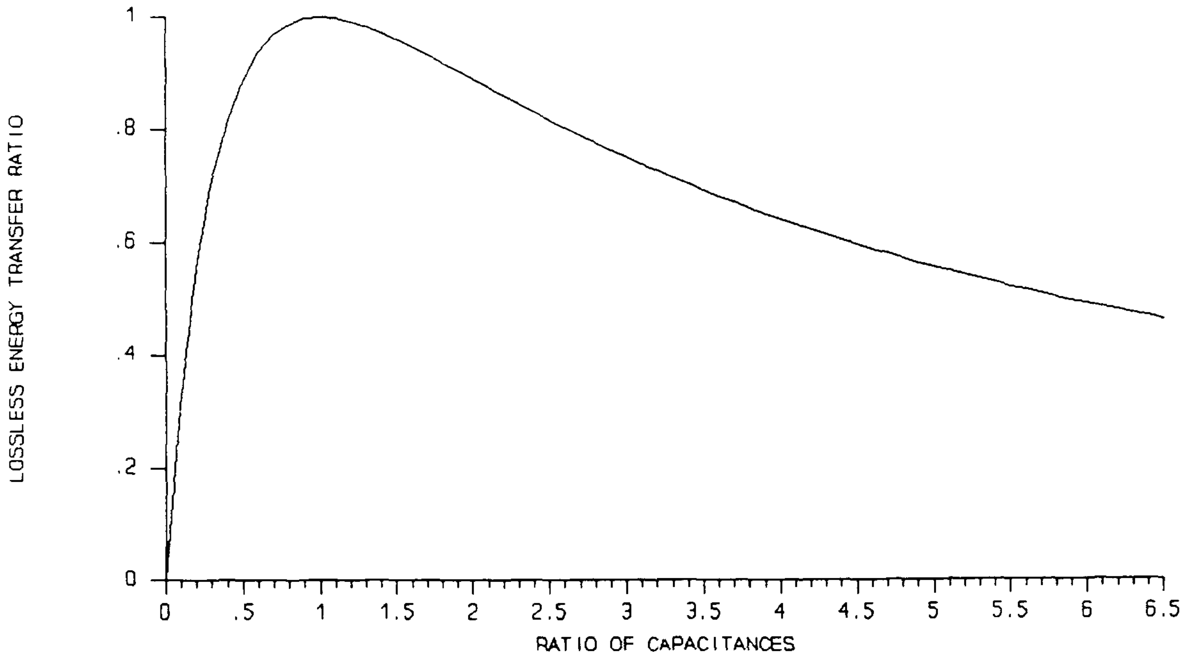
$V(C_1 \text{ minimum}) = [V_0/(C_1 + C_2)](C_1 - C_2e^{-\pi/2\omega\tau})$

$Q = (L/C)^{1/2}/R$ = Circuit Quality Factor

Energy transfer to C_2 as a fraction of original C_1 energy η

$\eta = [C_1C_2/(C_1 + C_2)^2](1-e^{-\pi/2\omega\tau})^2$

Efficiency of lossless energy transfer from C_1 to C_2.



3) Overdamped case

$$R^2 > 4L/C$$

$$I = (V_0 e^{-t/2\tau}/2L\omega)[e^{+\omega t} - e^{-\omega t}]$$

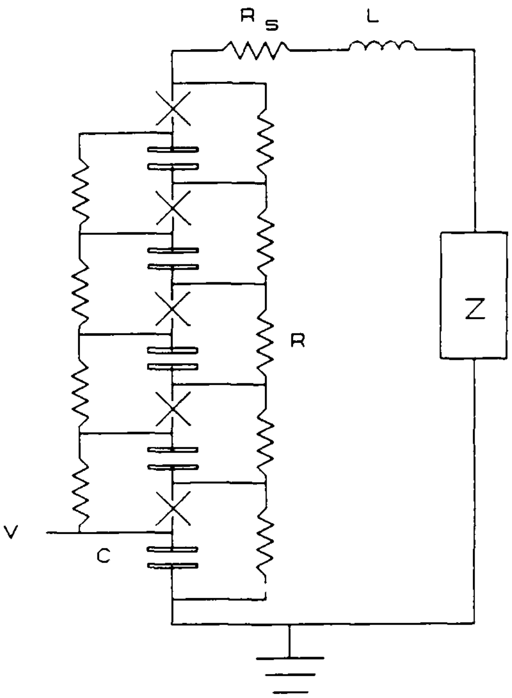
$$V(C_2) = (V_0/2C_2L\omega)\{2\omega/\omega_0^2 - e^{-t/2\tau}[(e^{-\omega t}/(\omega+(1/2\tau))) + (e^{\omega t}/((1/2\tau) - \omega))]\}$$

3) Shunt resistance (Underdamped) may be important in the case of water capacitors or the charge resistors in Marx generators. For the underdamped case, a resistance shunting C_2 of value Rs may be included in the output voltage equation as given below:

$$V(C_2)=[V_0C_1/(C_1+C_2)]\{\exp(-t/R_s(C_1+C_2))-\exp(-(t/2\tau+t/2R_sC_2))[\cos\omega t+(1/2\omega\tau)\sin\omega t]\}$$

3.2 Marx Generators

3.2.1 Conventional Marx



N = Number of capacitor stages
C_2 = Capacitance to be charged
$L = L_{switches} + L_{caps} + L_{connections}$
$R_s = R_{switches} + R_{caps}$
$\tau = L/R_s$
C = Capacitance of single stage
$\omega^2 = ((NC_2 + C)/(NLCC_2) - 1/(2\tau)^2)$

Capacitive load (Blumlein, Pulse line, etc.) = C_2

$V(C_2 \max) = [2NV_oC/(C+NC_2)]\{1\text{-}e^{-\pi/2\omega\tau}\}$

<u>Losses When Charging</u> with resistance R or inductance L_c per stage for N stages, the loss energy E_ℓ during the discharge is approximately:

$E_\ell = N(V_o^2/R)(\pi/\omega)$

$E_\ell = N(V_o^2/L_c)(\pi/2\omega)^2$

For more detailed information use the data of section 3.1.1 with the substitutions C_1 = C/N.

<u>Resistive load</u> R_L, where $R_s = R_L$ plus the sum of all other series circuit resistances

$\omega^2 = ((R_s/2L)^2 - N/(LC))$
$\tau = L/R_s$

$V_{out} = (NV_oR_Le^{-t/2\tau}/2L\omega)[e^{+\omega t} - e^{-\omega t}]$

$T_m = (1/2\omega)\ln[(1 + 2\omega\tau)/(1 - 2\omega\tau)]$ = time at which voltage is peak

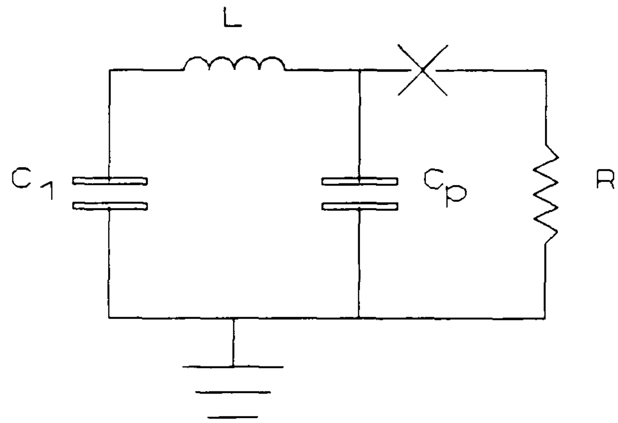
<u>Losses</u> due to charging components for inductive and resistive charging during the discharge--specifically energy dissipation in the 2N charge resistors R during the pulse, or energy left in the 2N charge inductors L_c at the end of the pulse:

$E_\ell = NV_o^2R_s(R_s^2C/2L - 1)/(R[(R_s^2/4L)\text{-}N/C])$

$E_\ell = (V_o(R_L + R)C)^2/NL_c$

Peaking circuit

Peaking circuits are used in order to get fast rise times from Marx based circuits for applications such as EMP testing. In EMP testing, an exponential waveform with a very fast rise time is required. Note that source resistances are ignored in this treatment, and that these may be included by referring to the treatment of 3.1.1.



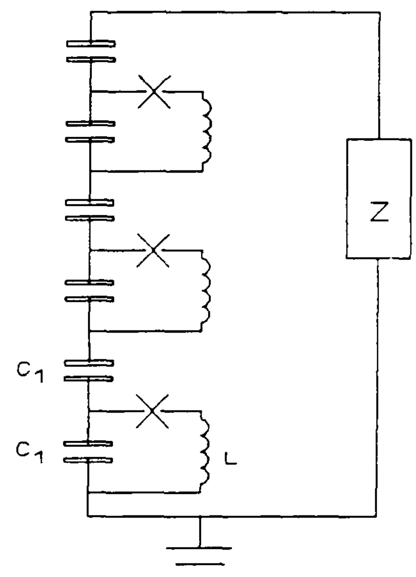
$$C_p = (L/R^2)/(1+(L/R^2C_1))$$

is the peaking capacitance required to give an exactly exponential decay through the load resistance R. The switch is arranged to fire when the current is maximum at

$$t = (LC_pC_1/(C_1 + C_p))^{1/2} \cos^{-1}(C_p/C_1)$$

LC Marx

'Vector Inversion Type'



Open circuit voltage

$$\omega^2 = 1/LC, \ \tau = L/R$$

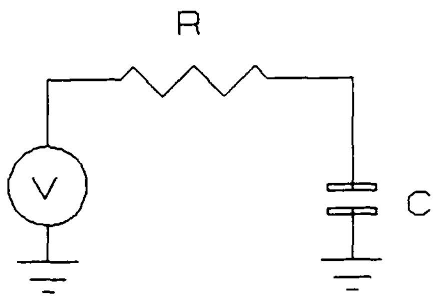
$$V = (nV/2)(1-e^{-t/2\tau}\cos\omega t)$$

3.3 Capacitor Charging Circuits

TYPE	Application	Advantages	Disadvantages
Resistive, No filter Capacitor	Low voltage, Small Caps.	Simple	Low eff. (50%)
Resistive, w/filter Capacitor	High power, Low-intermed. voltage		High stored energy
Inductive	Pulse charging	Efficient Doubles voltage	Requires store capacitor, 1st pulse half voltage
Pulse Transformer	High voltage pulse charging	Efficient	Complex, Expensive
Resonant Pulse	High voltage pulse charging	Efficient	Complex, Capacitors undergo reversal
AC resonant	Pulse charge	Efficient	Not versatile

3.3.1 Resisistive Capacitor Charging, Constant Voltage Power Supply

R = charge resistance
V_o = power supply voltage
C = capacitance to be charged



$$V(t) = V_o (1 - e^{-t/RC})$$

$$I(t) = V_o e^{-t/RC}$$

V/V_o (%)	t/RC
50	0.7
75	1.4
90	2.3
95	3.0
99	4.6
99.9	6.9

3.3.2 Resonant Charging

C_1 = Storage capacitance
C_2 = Load capacitance
L = Charging inductance
V_1 = Initial voltage on C_1
$\omega^2 = (C_1 + C_2)/LC_1C_2$
V_2 = Final voltage on C_2

$I(t) = (V_1/\omega L)\sin\omega t$, where

$V_2(t) = (C_1 + C_2))\ (1 - \cos \omega t)$

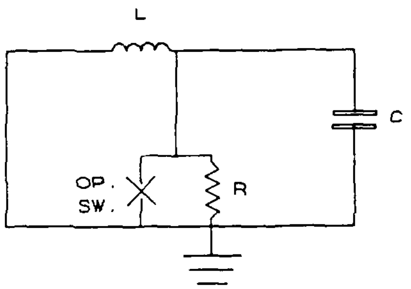
$V_2max = GV$, where ringing gain, $G = 2C_1/(C_1+C_2)$

also see section 3.1.1

<u>Inductive store charging a capacitance</u> using an opening switch

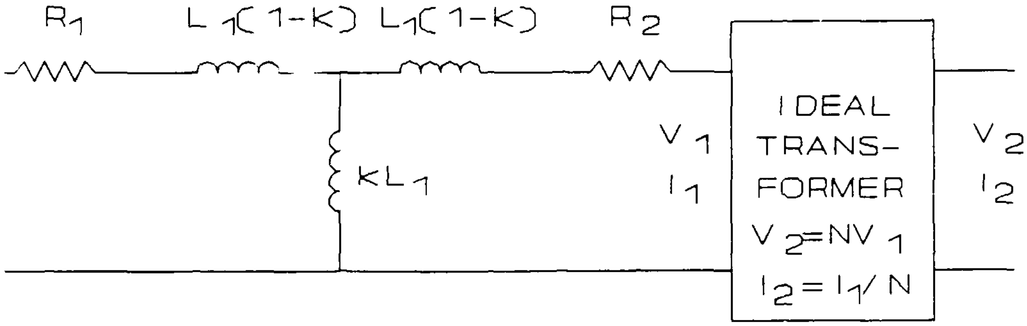
I_0 = Initial Current
$\omega^2 = LC - (1/4R^2C^2)$
$\tau = RC$
R = Circuit total Resistance
C = Capacitance to be charged

$V_2(t) = (I_0/\omega C)e^{-t/2\tau}\sin\omega t$



3.4 Transformer Based Application Circuits

3.4.1 Transformer Equivalent Circuit (suggested by I.D. Smith)



A number of transformer equivalent circuits exist, and they often differ in their details. In particular, many of the circuits are unable to treat coupling coefficients much less than 1. For transformers made from sheets, the current distribution in the sheet must be assumed to remain fixed in time for this model to be appropriate. In making measurements of equivalent circuit parameters, frequencies used must be close to those in actual use, and the effect of stray components must be quantified. For magnetic core transformers, measurements may need to be made in actual pulsed conditions since permeability can be a strong function of magnetizing current. The calculated turns ratio should be used instead of the counted turns ratio in the calculations below.

L_1 = Primary inductance (measured with the secondary open)
L_2 = Secondary inductance (measured with the secondary open)
M_1 = Mutual inductance referred to primary side
k = Coupling coeficient
R_1 = Primary series resistance
R_2 = Secondary series resistance

The equivalent circuit parameters are measured or computed as follows. All quantities are referred to the primary side except where indicated by an asterisk:

$N = (L_2/L_1)^{1/2}$
$L_2 = L_2^*/N^2$
L_{ps} = primary inductance with the secondary shorted = primary leakage inductance
L_{ss}^* = secondary inductance the primary shorted = secondary leakage inductance
$N^2 = L_{ss}^*/L_{ps}$ is a useful consistency check
$R_2 = R_2^*/N^2$
$k = (1 - L_{ps}/L_1)^{1/2} = (1 - L_{ss}/L_2)^{1/2}$
$M^* = k(L_1 L_2^*)^{1/2}$
$M_1 = k(L_1 L_2)^{1/2}$
ℓ = Magnetic path length of core = $2\pi r$ for a toroidal core
H = Magnetization of the core = $(N_1 I_1 - N_2 I_2)/\ell$

Energy loss due to Magnetizing current = $E = [\int V dt]^2/2kL_1$

In general, the capacitances can be ignored in the circuit model unless the load capacitance is low. Winding resistances are usually important, as are the inductances.

3.4.2 Generalized Capacitor Charging

General capacitor charging relations for arbitrary coupling coefficient, and primary and secondary capacitances. Losses are assumed to be negligible in these formulae

Voltage on charging capacitor L_2:

$$V_2 = kV_0(\cos s_1 t - \cos s_2 t)/[(L_1 L_2)^{1/2} C_2\{\omega_1^4 - 2(1-2k^2)\omega_1^2\omega_2^2 + \omega_2^4\}]^{1/2}$$

$$s_1^2, s_2^2 = (1/(2-2k^2))\{\omega_{12} + \omega_{12} \pm [\omega_1^4 - 2(1-2k^2)\omega_1^2\omega_2^2 + \omega_2^4]^{1/2}$$

For $\omega_1 = \omega_2 = \omega$

$$V_2(t) = (L_1/L_2)^{1/2}(V_0/2)[\cos(\omega t/(1-k)^{1/2}) - \cos\omega t/(1+k)^{1/2}]$$

Dual Resonance occurs for $k = 0.6$, and V_2 is maximum at $t = 4/\omega$.
A family of dual resonance solutions exists for lower values of k, however, these are of less practical interest

3.5 Magnetic Switching

a = inner toroid diameter (m)
b = outer toroid diameter (m)
f = charge time/discharge time
E = energy in capacitor (joules)
$\delta B = B_r + B_s$
B_r = field at reset (tesla)
B_s = Saturation field (tesla)
g = packing fraction of magnetic material inside windings
N = number of turns
τ = charge time of the initial capacitor assuming inductively limited, capacitor - capacitor charging ($1 - \cos\omega t$ waveform)
= $\pi(LC/2)^{1/2}$ where L is the charging inductance

Minimal volume requirement for magnetic switching is that the relative magnetic permeability

$$\mu >> f^2$$

$$U = \pi^3 \times 10^{-7} E f^2 Q/(\delta B g)^2$$

= Required switch volume (m^3) for energy transfer between two equal capacitances

$Q = 1$ for strip type magnetic switches, or thin annulii

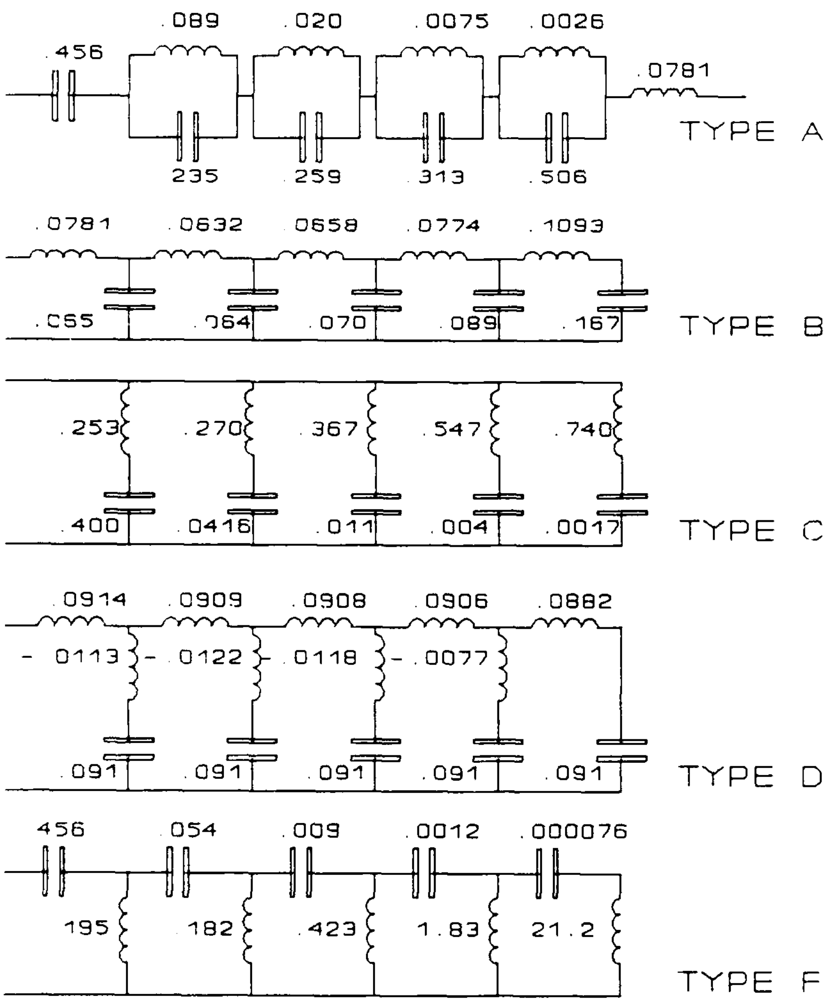
$Q = \ln(b/a)[(b+a)/2(b-a)]$ for general toroid case

$N = \pi V \tau (b+a)/2g\delta BU$

4.0 TRANSMISSION LINES AND PULSE FORMING NETWORKS

4.1 Discrete Pulse Forming Networks

A variety of pulse forming networks have been developed in order to produce output pulses with a constant, or near constant amplitude for the pulse duration. The ideal physical transmission line may be approximated by an array of equal series inductors and capacitors as shown below. The examples below are optimized 5 element networks which produce the minimum amount of pulse ripple when charged and discharged. These pulse forming networks are discussed in great detail in the work of Glasoe and Lebacz.



Five section Guilleman voltage-fed networks. Multiply the printed inductance values by $Z\tau$, the capacitances by τ/Z where Z is the line impedance, and τ is the pulse duration. Zero mutual inductance is assumed in the calculations.

4.2 Transmission Line Pulsers

Ideal pulse line of impedance Z connected to a load of resistance R

V_0 = open circuit voltage of the pulse line
τ = L/(Z + R)
L = total inductance (switch + connections, etc.)
ℓ = physical length of line for continuous line

T = $2\ell\epsilon^{1/2}/c$
n = cycle number
ϵ = relative permittivity of the medium

$$I = V_0(1 - e^{-t/\tau})/(Z + R)$$

$$V = V_0 R(1 - e^{-t/\tau})/(Z + R)$$

Rise time from .1 max V to .9 max V = 2.2τ

The 'plateau' value of load voltage (ignoring rise time effects) changes at time intervals of T. The nth amplitude (where n starts with 0) is:

$$V(t = nT + T/2) \simeq V_0 R(R-Z)^n/(R + Z)^{n+1}$$

Blumlein response

Ideal Blumlein of impedance Z in each half line, with length ℓ in each half

L = switch plus connection inductance
τ = L/Z
n = cycle number

$$I_{sw} = 2V_0(1 - e^{-t/\tau})/Z$$

$$V = V_0 R(1 - e^{-t/\tau})/(2Z + R)$$

$$V(t = 2nT + T/2) = V_0 R(R - 2Z)^n/(R + 2Z)^{n+1}$$

$$V(t = 2nT + 3T/2) = 0$$

5.0 ELECTRICITY AND MAGNETISM

Variables:

L, Inductance (Henries)

ℓ, Length (m, meters)

Z_o=377 Ohms=μ_o/ϵ_o

c=Speed of light=3.0(8)m/sec

C, Capacitance (Farads)

Z, Impedance (Ω, Ohms)

ϵ, Rel. dielectric Const.

$\tau=2\ell\epsilon^{1/2}/c$=pulse length of line

5.1 Transmission Line Relationships-General:

$C=\epsilon^{1/2}\ell/Zc$ $\quad L=Z\ell\epsilon^{1/2}c$ $\quad LC=\ell\epsilon/c$

$C=\tau/2Z$ $\quad L=Z\tau/2$ $\quad \tau=2(LC)^{1/2}$

Specific Common Transmission Lines

Coaxial, a=ID, b=OD, $Z=(Z_o/2\pi\epsilon^{1/2})\ell n(b/a)$

Parallel Wires, d=wire diam, D=Wire center spacing $Z=(Z_o/\pi\epsilon^{1/2})\cosh^{-1}(D/d)$

Wire to ground, d=wire diam, D=Wire center-ground spacing

$Z=(Z_o/2\pi\epsilon^{1/2})\cosh^{-1}(2D/d) \sim (Z_o/2\pi\epsilon^{1/2})\ell n(4D/d)$, for $D >> d$

Parallel Plate, Width w, Separation d, $d < w$

$Z \simeq Z_o\epsilon^{1/2}d/(d + w)$

Circuit Parameter Formulas

Coaxial Inductor, b=OD, a=ID $L=(\mu_o\ell/2\pi)\ell n(b/a)$

Solenoid,

- ℓ = solenoid length (m)
- r = solenoid radius (m)
- n = turns per meter, $N=\ell n$
- t = solenoid thickness (m)
- z = distance between field point and one end of solenoid (m)
- V = Volume of the solenoid (m^3)

Ideal solenoid, where $\ell >> r$

$L = \mu_o n^2\ell\pi r^2 = 1.26n^2\ell\pi r^2=4N^2r^2/\ell$ microhenries

B = mag. field = $1.26 \times 10^{-6}nI$

$P = (B^2\rho/\mu_o{}^2)V(2t/r)$ = Power dissipation of an ideal DC solenoid

Non-ideal solenoid

$B = (\mu_o nI/2)[z/(z^2 + r^2)^{1/2} + (\ell-z)//\{(\ell-z)^2 + r^2\}^{1/2}]$

Magnetic Field of a Long Wire

r=distance from wire center(m), $B=(\mu_0/2\pi)I/r=200(I(\text{kiloamps})/r(\text{cm}))$gauss

Inductance of a Current Loop

$L = N^2(a/100)[7.353\log_{10}(16a/d)-6.386]$ microhenrys

a=mean radius of ring in inches, d= diameter of winding in inches, and $a/d > 2.5$

5.2 Skin Depth and Resistivity

Skin depth δ is the depth at which a continous, tangential sinusoidal magnetic field decays to 1/e times the incident field.

$\omega=2\pi f$
μ=permeability of medium
ρ=material resistivity (Ω-m); ρ_c = 1.7(-8)Ωm(copper)

$$\delta=(2\rho/\omega\mu)^{1/2}=(6.61/f^{1/2})((\mu_0/\mu)(\rho/\rho_c))^{1/2}$$

Resistance per square R_{sq} is the resistance of the surface for a length equal to the width at a given frequency

ℓ = length
w = width

$$R = R_{sq}\ell/w$$
$$R_{sq} = \rho/\delta=(\omega\mu\rho/2)^{1/2}$$
$$R_{sq} = 2.61(-7)f^{1/2}((\mu/\mu o)(\rho/\rho_c))^{1/2}$$

High frequency resistance of an isolated cylindrical conductor

D = Conductor diameter in inches
R_{ac} = Effective resistance for a CW ac wave

Note that R_{ac} is somewhat smaller for unipolar pulses than for ac.

If $Df^{1/2}(\mu_r\rho_c/\rho)^{1/2} > 40$:

$$R_{ac} \simeq (f^{1/2}/D)(\mu_r\rho/\rho_c)^{1/2} \text{ X } 10^{-6} \text{ ohms/ft.}$$

If $Df^{1/2}(\mu_r\rho_c/\rho)^{1/2} < 3$, then $R_{ac} \sim R_{dc}$

5.3 Field Enhancement Functions in Various Geometries

Cylindrical Geometry where X is the distance between two conductors, and r is the radius of the smaller conductor.

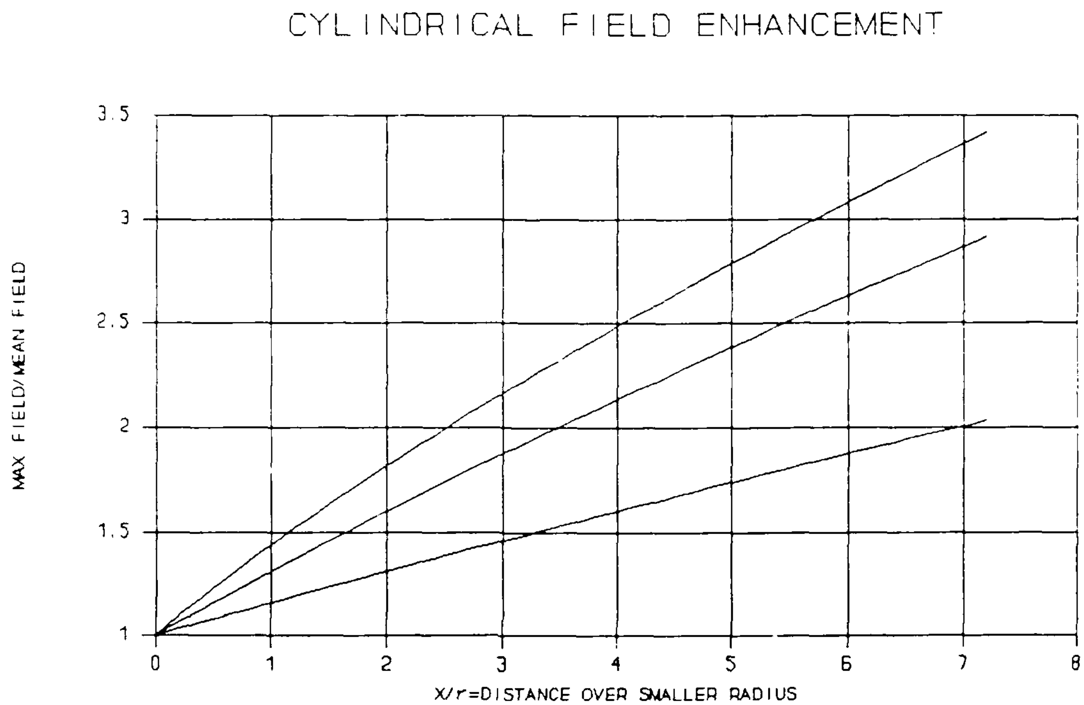


Figure 10. Field enhancement factor for cylindrical geometry configurations. Upper curve: coaxial line, Intermediate curve: two equal diameter wires, Lower curve: conducting wire adjacent to a plane.

Maximum field strength equations for Cylindrical Geometry:

b = outer cylinder radius

$E = V/(r \ln(b/r))$ Concentric cylinders

$E = V(D^2-4r^2)^{1/2}/[2r(D-2r)\ln\{(D/2r)^2 + ((D/2r)^2-1)^{1/2}\}]$

where D = X + 2r for parallel cylinders, and D = 2X + 2r for a cylinder spaced X from a uniform ground plane and parallel to it

Semicylinder on a plane E_m = 2E where E is the applied electric field

Spherical Geometry

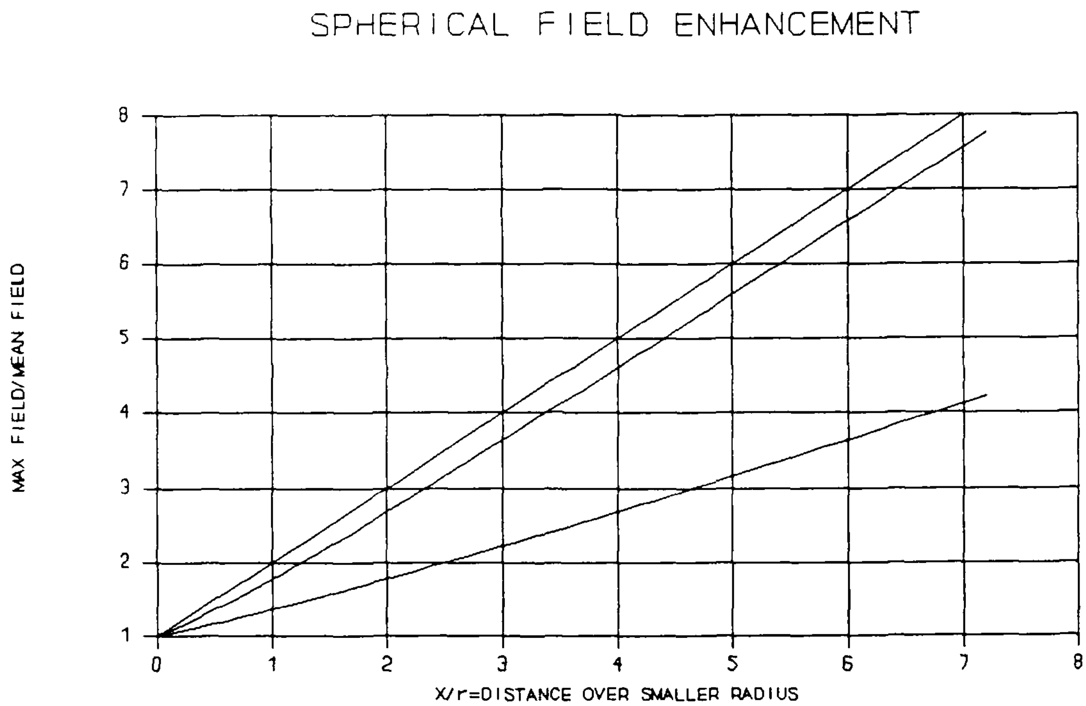


Figure 11. Field enhancement factors for Spherical geometry. Upper Curve: Nested spheres, Intermediate Curve: Adjacent Spheres, Lower Curve, Sphere-Adjacent ground.

Maximum field strength equations for Spherical geometry.

R = outer sphere radius
r = inner sphere radius

$E = VR/r(R-r)$ Concentric spheres

$E = V[(X/r) + 1 + ((X/r) + 1)^2 + 8)^{1/2}]/4X$ Equal spheres spaced X

$E = V[(2X/r) + 1 + ((2X/r) + 1)^2 + 8)^{1/2}]/8X$ Sphere of radius r spaced X from a ground plane

Hemisphere on a plane in a uniform field of amplitude E

$E_m = 3E$

6.0 MATERIALS PROPERTIES

The dielectric properties of gases and liquids are well understood (empirically), and are presented as such. The typical values of dielectric strength for solids are an exception to this understanding. Solid breakdown depends on preparation, pulse life requirements, and the medium in which the solid is contained. The values quoted in this document for solid breakdown actually refer to long term working strength, and must be considered to be of limited value. Note that in general, the dielectric strength of all materials decreases with increasing sample thickness. ϵ is the relative permittivity below, and tan δ is the energy loss per cycle.

6.1 Solid Dielectric Properties

Material	Diel. Const. 60 Hz. ϵ	tan δ	Diel. Const. 1 MHz. ϵ	tan δ	Diel. Strength* V/mil
Aluminum Oxide	8.80	3.3(-4)	8.80	320	320
Barium Titanate	1250	0.056	1143	0.0105	75
Soda-Borosilicate Glass	4.97		4.84	3.6(-3)	400
Epoxy (Epon RN-48)	4.50	0.05	3.52	0.0142	800
Polycarbonate	3.17	0.009	2.96	0.01	400
Acrylic	4.0	0.016		2.550.009	400
Polyimide	3.4	0.002	3.4	0.003	570
Polyvinyl Chloride	3.20	0.0115	2.88	0.016	400
PTFE (Teflon)	2.10	<5(-4)	2.10	<2(-4)	550
Nylon	8	4.10	3.40	0.04	350
Polyethylene	2.26	<2(-4)	2.26	<2(-4)	450
Polypropylene	2.55	<5(-4)	2.55	<5(-4)	650
Paper	3.30	0.010	2.99	0.038	200

*Typical DC values for .10 inch thick samples

6.2.1 Gas Properties

Gas breakdown, DC to
approximately 1 microsecond

$E = 24.5p + 6.7(p/R_{eff})^{1/2}$ kV/cm. Air

R_{eff} = .115R for spheres, and .23R for cylinders, and the gap distance for planar geometries, where p is the pressure in atmospheres

Resistive phase duration of an air arc

$\tau = 88p^{1/2}/(Z^{1/3}E^{4/3})$ nanoseconds

where p is the pressure in atmospheres, E is the electric field in MV/m, and Z is the characteristic impedance of the circuit.

Relative electric strengths:

Relative breakdown field compared to air	
Air	1.0
Nitrogen	1.0
SF_6	2.7
Freon gas	2.5
Hydrogen	0.5
30% SF_6, 70% air (by volume)	2.0

Paschen's Law

Under most circumstances, the breakdown of gases is a function of the product of pressure (p) and gap length (d) only, where this function depends on the gas.

$V = f(pd)$

The breakdown strength of a gas is monotonic decreasing below a specified value of pd = $(pd)_{crit}$ and monotonic increasing above that value. The values of $(pd)_{crit}$ and the breakdown voltage at that value of pd are given below:

GAS	pd_{crit} (Torr-cm)	$V(pd_{crit})$ (Volts)
Air	0.567	327
Argon	0.90	137
Oxygen	0.70	450
Helium	4.0	156

760 Torr = 1 standard atmosphere

6.3 Liquid Breakdown

t = time that the pulse is above 63% of peak voltage (μsec)
A = Stressed area (cm^2)
d = gap between electrodes
E = Electric field (MV/cm)

Pulse Breakdown of Liquids

Transformer Oil

$E_+ = .48/(t^{1/3}A^{.075})$ (Positive Electrode)

$E_- = 1.41E_+\alpha$ (Negative Electrode)

$\alpha = 1 + .12[E_{max}/E_{mean}) -1]^{1/2}$

Note: The above formulae do not apply if a DC pre-stress (> 500V/cm) is applied accross the gap

Water (areas > 1000 cm^2)

$E_+ = .23/(t^{1/2}A^{.058})$ (Positive Electrode)

$E_- = .56/(t^{1/3}A^{.070})$ (Negative Electrode)

$\alpha = 1 + .12[E_{max}/E_{mean}) -1]^{1/2}$

Resistive rise time of an oil switch

$\tau_r = 5\rho^{1/2}/Z^{1/3}E^{4/3}$ where ρ is the density of the liquid, and E is the electric field in MV/m

General comments on Breakdown of Transformer Oil

Pulse power operation (typical) 100-400 kV/cm for pulsed operation with no DC prestress. The exact value is dependent on the oil, and field enhancements. For conservative DC operation 40 kV/inch is generally a reliable guideline. This value generally allows the user to ignore field enhancements and dirt when designing the DC system. If carbon streamers form in the oil during a pulse, these values no longer apply. Filtration and circulation are required in oil to avoid carbon build-ups.

6.4 Vacuum Insulation and Surface Flashover

We assume in this section that the pressure is below 10^{-4} Torr, and note that variations due to the residual gas pressure are observed at pressures as low as 10^{-6} Torr.

d = individual insulator length (cm.)
A = insulator area (cm^2)
t = pulse duration or pulse train duration (μsec)

Pulsed 45 degree acrylic insulators in vacuum

$E = 175/(t^{1/6}A^{1/10})$ kV/cm. typical for 1-2" long insulators, and more than 5 insulators

$E = 33/(t^{1/2}A^{1/10}d^{0.3})$ kV/cm for bipolar pulses

DC Flashover

Material	Electric field (kV/cm.)
Glass	$18/d^{1/2}$
Teflon	$22/d^{1/2}$
Polystyrene	$35/d^{1/2}$

Vacuum breakdown

Vacuum breakdown between parallel electrodes depends on surface preparation, pulse length electrode history, and possibly gap length, as well as material type.

We list typical values below primarily in order to give the reader an ordering of material strength. The typical voltage at which the data below is applicable is 500 kV.

Material	Pulse Breakdown (kV/cm.) 100 ns.
Aluminum	290
Graphite (Poco)	175
Lead	170
Molybdenum	460
Stainless Steel	300
Velvet cloth	20-50

A variation of breakdown strength with gap length of $d^{-0.3}$ may be inferred from some data, however this effect is more pronounced in DC high voltage breakdown.

6.5 Conductor Properties

Conductivities of Conductors

Material	Density (gm/cm^3)	Resistivity(20C) (10^{-6}ohm-cm)	Ht. Cap. (J/gmC)	Temp. Coef. (1/C)
Aluminum	2.70	2.62	.946	0.0039
Beryllium	1.85	35	1.78	0.0042
Bismuth	9.80	115	0.123	0.004
Brass (66Cu,34Zn)	8.40	3.9	0.418	0.002
Chromium	7.19	2.6	0.460	
Copper	8.96	1.72	0.418	0.0039
Graphite(typical)	2.25	1400	0.894	-0.0005
Gold	19.3	2.44	0.130	0.0034
Indium	7.31	9	0.238	0.0050
Iron	7.87	9.71	0.452	0.0057
Lead	11.34	21.9	0.126	0.004
Magnesium	1.74	4.46	1.04	0.004
Nichrome(65Ni,12Cr,23Fe)		100	0.00017	
Nickel	8.9	6.9	0.268	0.0047
Silicon	2.4	85,000	0.736	
Silver	10.5	1.62	0.234	0.0038
Stainless Steel	7.90	90		
Steel(.5%C)	13-22	0.520	0.003	
Tantalum	16.6	13.1	0.151	0.003
Tin	7.3	11.4	0.226	0.0042
Titanium	4.54	47.8	0.594	
Tungsten	19.3	5.48	0.142	0.0045

6.5.1 Wire Data–Standard Sizes of Copper Wire

AWG B&S GAUGE	DIAM. (MILS)	OHMS PER 1000 FT	LB. PER 1000 FT
0000	460	.049	640
000	410	.062	509
00	365	.078	403
0	324	.099	318
1	289	.124	253
2	257	.157	200
3	229	.198	159
4	204	.249	126
5	182	.313	100
6	162	.395	79.4
7	144	.500	62.8
8	128	.633	49.6
9	114	.798	39.3
10	102	.997	31.5
11	90.7	1.26	24.9
12	80.8	1.59	19.8
13	72.1	1.99	15.7
14	64.1	2.52	12.4
15	57.1	3.18	9.87
16	50.8	4.02	7.81
17	45.3	5.05	6.21
18	40.3	6.39	4.92
19	35.9	8.05	3.90
20	31.2	10.7	2.95
21	28.5	12.8	2.46
22	25.4	16.1	1.95
23	22.6	20.3	1.55
24	20.1	25.7	1.22
25	17.9	32.4	.970
26	15.9	41.0	.765
27	14.2	51.4	.610
28	12.6	65.3	.480
29	11.3	81.2	.386
30	10.0	104	.303
31	8.93	130	.241

6.6 Magnetic materials

Material	Sat. flux kG B_s	Res. Flux kG B_r	Init. perm. DC μ_i	Max. perm. DC μ_m	Resistivity ohm-cm ρ
Metglas					
2605SC	16.1	14.2	8,000	300,000	142(-6)
2605CO	18.0	16.0	5,000	250,000	160(-6)
3% Si-Fe	16.5	14-15	500	25,000	50(-6)
Permalloy	7.5	6.0	20,000	150,000	45(-6)
50% Ni-Fe	16.0		2,500	25,000	45(-6)
NiZn Ferrite					
TDK PE11B	3.5	2.9	2,000		1(11)
Ferroxcube					
4C4	3.0	2.7	125	350	
MnZn Ferrite					
Ceramic					
Magnetics					
MN80	5.0	2.5	1,500	5,000	200

Note that the data above are applicable for low frequencies, and the performance at higher frequencies is dependent on frequency. Metal materials must be wound in thin insulated tapes for most pulse power applications. Materials above can all be used (generally with lower μ) in the microsecond range.

6.6 Components

6.6.1 Capacitors

N = number of pulses to failure
E = Electric field in application
V_b = DC breakdown voltage
d = dielectric thickness
Q = circuit quality factor
β = thickness exponent, typically less than 3
V_r = reversal voltage

$N \propto (Ed/V_b)^{-8} d^{-\beta} Q^{-2.2}$ for plastic capacitors

$N \propto (Ed/V_b)^{-12} Q^{-2.2}$ for ceramic capacitors

$V_r = 1 - \pi/2Q$

Notes: Barium Titanate capacitors--unless specially prepared--vary in capacitance by about a factor of 2 over their range of voltage utilization

Mica capacitors have an excellent combination of dissipation factor, and low change in value under voltage and temperature stress, but only at high cost.

Paper and plastic capacitors can have significant internal inductance and resistance, and these quantities must be ascertained in any critical application. In practice it is nearly impossible to discharge any paper or plastic capacitor in less than 100 ns, and many capacitors may take much longer to discharge.

6.6.2 Resistors

General comments on performance under pulse power conditions.

Carbon composition resistors have excellent performance in voltage and power handling, but may have resistance variations with voltage of 2 -50 % depending on type, history, etc.

Metal film resistors must be specially designed for high voltage and pulse power use. The pulse energy handling capability of film resistors is generally inferior to that of bulk resistors due to the relatively small mass of the current carrying component.

Liquid resistors such as water/copper sulphate, etc, are subject to variation in resistivity with time. The preferred method for measuring the resistance of these components is with a pulsed high voltage (measuring current for a known voltage). DC measurments at low voltage can often be wrong by factors of 2 or 3.

7.0 APPLICATIONS

7.1 Intense Electron and Ion Beam Physics

Space charge limited electron emission current, or 'Child-Langmuir' current density

V = Voltage applied in MV
d = gap between anode and cathode in cm.

J_s = Current density = $2.34V^{3/2}/d^2$ kA/cm^2 for V < .5 MV

$J_s = 2.7[(V/0.51 + 1)^{1/2} - 0.85]^2/d^2$ kA/cm^2 for V > .5 MV

Bipolar flow in an anode-cathode gap where the anode is also a source of space charge limited ions

$J = 1.84\ J_s$ (V < .5 MV)

$J = 2.14\ J_s$ (V > .5 MV)

Typical thermionic emitter data

Material	efficiency (mA/watt)	typ. J (amps/cm^2)	Temperature (Kelvin)	hot R/cold R R = Resistance
Tungsten	5-10	.25-.7	2550	14/1
Thoriated Tungsten	40-100	0.5 - 3.0	2000	10/1
Tantalum	10-20	0.5-1.2	2450	6/1
Oxide	50-150	0.5-2.5	1100	
Dispenser	100-2000	1.0-25	1400	

Vacuum beam propagation

Space charge limiting current

b = beam conducting drift tube diameter
a = beam outer diameter
f = ratio of ion to electron densities
g = ln(b/a) for annular beams
= 1/2 + ln(b/a) for solid beams
$\alpha = 1 + ea\delta B/mc = 1 + a\delta B/1.7$
δB = change in magnetic field (kG in numerical formula) giving rise to rotation
$\gamma = 1 + V/0.51 = 1/(1-\beta^2)^{1/2}$ = relativistic factor
$\beta = v/c$ = normalized beam velocity
$I_o = 4\pi mc/\mu_o e$ = 17,000 amperes

$I < 17(\gamma^{2/3} - \alpha^{2/3})^{3/2} /(1-f)g$ kiloamperes

Uniform beam spread curve

$K = (2I/17\beta^2\gamma)[1/\gamma^2 - f]$
$\alpha = dr/dz$
a_o = initial beam radius

$r/a_o = \exp(\alpha^2/2K)$

Beam equilibrium condition

$I < 0.7\beta_p B^2 a^2 \gamma$ kA

β_p is the component of β in the direction of beam propagation, B is in kG, and a is in cm.

Magnetic field energy required to focus a beam in equilibrium (note that this may not assure stability)

k_1 = ratio of field coil radius to beam radius
k_2 = ratio of field to minimum field
k_3 = ratio of field energy inside coil radius to field energy outside coil radius
ℓ = length of field region (cm.)
E = Energy of magnetic field (joules)

$E = .036I\ell k_1^2 k_2^2 k_3/\beta_p\gamma$

Beam rotation

$\omega_c = 2\pi f_c = eB/\gamma mc = 17B/\gamma$ Ghz. = cyclotron angular frequency

where B is in kG

$r_L = \beta c/\omega_c = 1.7(\gamma^2 - 1)^{1/2}/B$ cm.

Cusp Condition

$\delta B = B_{initial} - B_{final}$ in kilogauss

$r < 3.4\ (\gamma^2 - 1)^{1/2}/\delta B$

Magnetic Insulation

d = anode-cathode gap in cm. for planar geometry
= $(b^2 - a^2)/2a$ in cylindrical geometry (b=OD, a=ID)

$B > (1.7/d)(\gamma^2 - 1)^{1/2}$ kG

Self magnetic insulation

Minimum current = $I = 8.5(\gamma^2 - 1)^{1/2}/\ln(b/a)$ Kiloamps

$= (I_0/2)(\gamma^2 - 1)^{1/2}/\ln(b/a)$

7.2 Electron Beam/Matter Interaction

Stopping Power and Range

Note that electron beams do not have a well defined stopping point in material. The CSDA range follows the path of an electron ignoring scattering, and is the longest distance an electron can physically travel. The practical range is the linear extropolation of the depth-dose curve and indicates a point where the electron flux is a few percent of the incident flux. Electron ranges and stopping powers are approximately proportional to the electron density in the medium, and are quoted for aluminum below.

Electron energy (MeV)	CSDA Range gm/cm^2	Practical Range g/cm^2
.1	.02	
.5	.25	0.16
1.0	.61	0.42
2.0	1.33	0.95
5.0	3.3	2.40
10.0	6.1	5.0

Radiation production with electron beams

100 ergs/gram = 1 Rad   10 Joules/gram = 1 MRad

For 1-10 MeV Aluminum, an approximate relationship for dose is: 1 μCoulomb/cm^2 gives rise to 0.2 megarads on average over the range

X-ray production efficiency

V = beam energy in megavolts
Z = Target atomic number
I = Beam current in kiloamperes

(X-ray energy total/Beam energy) = 7(-4)ZV

Dose rate D(rads/sec) at 1 meter directly ahead of the beam

$D = 1.7(6)IV^{2.65}$ for Z = 73

Blackbody Radiation Law

T = Temperature (Kelvin)
ϵ = Emissivity of surface

Radiation flux = $5.67(-8)\epsilon T^4$ W/m^2

7.3 High Power Microwaves

f(c) = (cutoff)frequency

c = speed of light = 3.0×10^8 m/sec
λ_g = waveguide wavelength
$\omega = 2\pi f$
$k = 2\pi/\lambda_g$

Frequency Band Designations:

Tri-Service		World War II Designations		
F(Ghz.)	Designation	F(Ghz.)	Designation	Waveguide
0.0-.25	A	.003-.030	HF	
.25-.50	B	.030-.300	VHF	
.50-1.0	C	.300-1.12	UHF	
1.0-2.0	D	1.12-1.76	L	WR650
2.0-3.0	E	1.76-2.60	LS	WR430
3.0-4.0	F	2.60-3.95	S	WR284
4.0-6.0	G	3.95-5.89	C	WR187
6.0-8.0	H	5.89-8.20	XN	WR137
8.0-10.0	I	8.20-12.9	X	WR90
10.0-20.0	J	12.9-18.0	Ku	WR6
20.0-40.0	K	18.0-26.5	K	WR42
40.0-60.0	L	26.5-40.0	Ka	WR28
60.0-100.0	M	40.0-60.0	U	WR19

Waveguide Relations

$f^2 = f_c^{\,2} + (c/\lambda_g)^2$

Rectangular Waveguide, dimensions a, b, a > b

$\lambda_g = 2a$ TE01, $\lambda_g = 2a/(1+(a/b)^2)^{1/2}$ TE11, $\lambda_g = 2a/(1+(a/b)^2)^{1/2}$ TM11,

$\lambda_g = 2a/(1+(a/2b)^2)^{1/2}$ TE21, $\lambda_g = 2a/(1+(a/2b)^2)^{1/2}$ TM21,

Circular Waveguide, a = radius

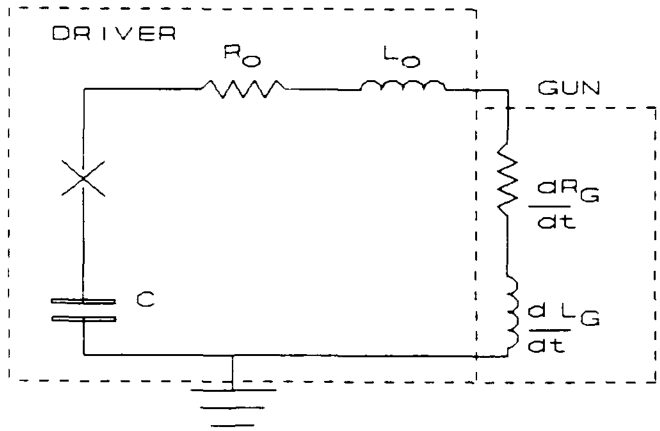
$\lambda_g = 1.640a$ TE01 $\lambda_g = 2.613a$ TM01

$\lambda_g = 3.412a$ TE11 $\lambda_g = 1.640a$ TM11

$\lambda_g = 2.057a$ TE21 $\lambda_g = 1.224a$ TM21

7.4 Railguns

Capacitor - Driven Rail Gun Circuit



Voltage: $(L_o + L_G)d^2q/dt^2 + (R_o + R_G + (dL_G/dx)v)dq/dt + q/C = V_o$

Eq. of Motion: $(m_p + (dm_a/dx)x)d^2x/dt^2 = (1/2)(dL_G/dx)(dI/dt)^2 - (dm_a/dx)(dx/dt)^2$

Electrode pressure: $P=(1/2)((dL_G/dx)/A)I^2$

for $dm_a/dx = 0$, I = constant: $v = [(dL_g/dx)Ix/m_pA]^{1/2}$

$R_G = R_{Go} + (dR_G/dx)x$

for $m = 0$, $I = Ie^{-\alpha t}\sin\omega t$, $L_G = L_{Go} + L_Gx$

C = driver capacitance
R_o = driver resistance (fixed)
L_o = driver inductance (fixed)
q = charge
A = cross-sectioned gun area
dR_G/dx = gun longitulinal resistance gradient
dL_G/dx = gun longitudinal inductance gradient
x = Longitudinal distance
v = Longitudinal projectile relocity
m_p = projectile mass
dm_a/dx = longitudinal air mass gradient

Ablation rate constants (Jerall V. Parker, Proceedings at the IEEE 3rd Symposimm on Electromagnetic Launch Technology, Austin, TX, 1988)

Gun Mode

Material	Ablation	Vaporization	Erosion (gas - liquid)
Copper	28 g/MJ	118 g/MJ	143 - 1630g/MJ
Tungsten	88	160	185 - 1575
Polyethylene	3.4	25	500 - 6,800
Lexan	5.6	40	
G-10	6.7	40	

8.0 DIAGNOSTICS

8.1 Sensitivity of an Unintegrated Square Current Loop

b = outer conductor distance to current source center(m)
a = inner conductor distance to current source center(m)
l = length of current loop(m) parallel to current axis
N = number of turns in the current loop

$V_{out} = (\mu_0 \ell N/2\pi)\ell n(b/a)(dI/dt)$

<u>Integrated</u> using a passive RC integrator

$V_{out} = (\mu_0 \ell N \ell n(b/a)/2\pi RC)I$

$= 2N\ell(\ell n(b/a)/RC)I$ ℓ is in cm., I in kA, RC in μsec

R = resistance of the RC integrator
C = capacitance of the RC integrator
RC product in seconds or microseconds as appropriate above
I = current to be measured

8.2 Rogowski Coil

The Rogowski coil consists of N turns wound on a form circular in shape evenly along the major circumference. Each turn has an area A. The major circumference has a radius ρ, and the output is independent of the relative position of the current flow as long as the current source is more than 2 turn spacings away from the current source.

ρ = major radius of the Rogowski coil

$V_{out} = (\mu_0 NA/2\pi\rho)dI/dt$	unintegrated
$V_{out} = (\mu_0 NA/2\pi\rho RC)I$	integrated
$= (2NA/\rho RC)I$	integrated A(cm^2), ρ(cm), RC(μsec), I(kA)
$= (12.63nA/RC)I$	integrated A(cm^2), RC(μsec), n(cm^{-1})

8.3 Current Transformer

Given appropriate frequency response in the core, a current transformer will give linear output over a wide range of time scales and currents.

R = total terminating resistance of the measurement circuit
b = od of square core
a = id of square core
ℓ = length of square core
δB = saturation magnetization of core
N = Number of turns
μ_0 = Permeability (H/m)

$V_{out} = (R/N)I$

$Z = R/N^2$ = insertion impedance of the current transformer

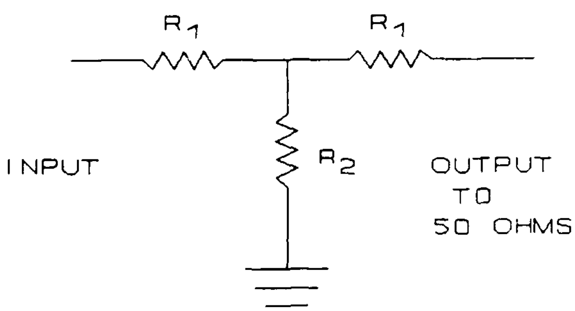
$\tau = \mu N^2 \ell \, \ell n(b/a)/R$ = exponential decay time of signal

$I_{max}\tau_{max} = N^2(b-a)\ell \delta B/R$

The risetime of current transformers is generally determined empirically

8.4 Attenuators

<u>T-pad type attenuators</u> are commonly used in fixed impedance (typically 50 ohm) systems. We list the general equation for this type of attenuator, and several standard values.



Z = characteristic impedance
K = attenuation factor (> 1)
= voltage out/voltage in
A = attenuation in decibels

$R_1 = Z[1 - 2/(K+1)]$

$R_2 = 2ZK/(K^2 - 1)$ $\qquad$ $A = 20 \, Log_{10}(K) = 10 \, Log_{10}(\text{Power in/Power out})$

<u>50 ohm attenuator combinations</u>

K	R_1	R_2
2	16.7	66.7
5	33.3	20.8
10	43.9	10.1

9.0 MECHANICAL DATA

9.1 Coarse Screw Threads

Size	Thds. per inch	Major diam. (inches)	Minor diam. (inches)	Lead Angle (deg.)	(min.)
1	64	0.073	0.056	4	31
2	56	0.086	0.067	4	22
3	48	0.099	0.076	4	26
4	40	0.112	0.085	4	45
5	40	0.125	0.098	4	11
6	32	0.138	0.101	4	50
8	32	0.164	0.130	3	58
10	24	0.190	0.145	4	39
12	24	0.216	0.171	4	1
1/4	20	0.250	0.196	4	11
5/16	18	0.313	0.252	3	40
3/8	16	0.375	0.307	3	24
7/16	14	0.438	0.360	3	20
1/2	13	0.500	0.417	3	7
9/16	12	0.563	0.472	2	59
5/8	11	0.625	0.527	2	56
3/4	10	0.750	0.642	2	40
7/8	9	0.875	0.755	2	31
1	8	1.000	0.865	2	29

9.2 Fine Threads

Size	Thds. per inch	Major diam. (inches)	Minor diam. (inches)	Lead Angle (deg.)	(min.)
0	80	0.060	0.465	4	23
1	72	0.073	0.058	3	57
2	64	0.086	0.069	3	45
3	56	0.099	0.080	3	43
4	48	0.112	0.089	3	51
5	44	0.125	0.100	3	45
6	40	0.138	0.111	3	44
8	36	0.164	0.134	3	28
10	32	0.190	0.156	3	21
12	28	0.216	0.177	3	22
1/4	28	0.250	0.211	2	52
5/16	24	0.313	0.267	2	40
3/8	24	0.375	0.330	2	11
7/16	20	0.438	0.338	2	15
1/2	20	0.500	0.446	1	57
9/16	18	0.563	0.502	1	55
5/8	18	0.625	0.565	1	43
3/4	16	0.750	0.682	1	36
7/8	14	0.875	0.798	1	34
1	12	1.000	0.910	1	36

9.3 Deflection of Beams

Rectangular Beams, d=vertical direction, l=length, b=wide direction, all units in inches, E=Elastic Modulus (lb/in^2)
W=Weight supported (pounds), h=deflection

Supported at both ends,	Uniform load	$h=5Wl^3/32Ebd^3$
Fixed at both ends,	Uniform load	$h= Wl^3/32Ebd^3$
Supported at both ends,	Center load	$h= Wl^3/4Ebd^3$
Fixed at both ends,	Center load	$h= Wl^3/16Ebd^3$

Deflection of Circular flat plates, R=radius(inches), W=total load (pounds), t=thickness (inches)

Edges supported,	Uniform load	$h=0.221\ WR^2/Et^3$
Edges fixed,	Uniform load	$h=0.054\ WR^2/Et^3$
Edges supported,	Center loaod	$h=0.55\ WR^2/Et^3$
Edges fixed	Centerload	$h=0.22\ WR^2/Et^3$

Metric Note: The formulae above also apply if the lengths are in meters, the weights are in kilograms, and the elastic modulus is in kg/m^2.

Modulus of elasticity

Material	Elasticity (Millions of lb/in^2)
Steel, (typical)	30
Steel, Stainless	28
Aluminum (most types)	10.3
Brass (typical)	15
Titanium	16
Acrylic	0.40
Nylon	0.30
Polyimide	0.37
Alumina	41
Macor	9.3
Wood	1.4 - 2.3

10.0 REFERENCES

These references are intended to reflect useful references in the field, and they might form a basic library. A short computerized database of references for this formulary is available (for the cost of postage and handling) from North Star Research Corporation.

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